Creating a System for Meeting the Fiber Requirements of Dairy Cows

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ABSTRACT

Current NRC recommendations for dairy cattle provide limited guidance to nutritionists for meeting the fiber and carbohydrate needs of lactating cows. The NRC provides only minimum recommendations for fiber and no accommodation for factors such as physical effectiveness of fiber, interactions with nonfibrous carbohydrates, or animal attributes, which can affect the optimality of dairy rations. To be an improvement, any new system for meeting the fiber requirements of dairy cows must be based on 1) feed characteristics that can be defined and preferably be determined quantitatively using routine laboratory methods and 2) animal requirements that correspond to critical feed characteristics and vary with feeding situation, ration composition, and attributes of the animal. Published data were used to develop coefficients for defining the physical effectiveness or roughage value of feeds and the fiber requirements of dairy cows. Information in this paper is intended to provide practical guidelines for improving current fiber recommendations and to serve as an idealized framework for future research on meeting the fiber requirements of dairy cows. The system is based on NDF as the measure of total chemical fiber in feeds. Adjustments for the effectiveness of NDF in maintaining milk fat production and optimizing ruminal fermentation are based on the particle size and inherent characteristics of NDF that affect chewing activity, ruminal pH, and milk fat production.
(**Key words**: roughage value, fiber requirements, neutral detergent fiber, chewing activity)

Abbreviation key: **A:P** = ratio of acetate to propionate, **eNDF** = effective NDF, **F:C** = ratio of forage to concentrate, **NFC** = nonfiber carbohydrates, **NSC** = nonstructural carbohydrates, **pef** = physical effectiveness factor, **peNDF** = physically effective NDF; **TNC** = total nonstructural carbohydrates.

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INTRODUCTION

Optimal utilization of diets by dairy cows is influenced by the chemical composition and physical characteristics of the ration. Carbohydrates often constitute 70% or more of the DM in dairy rations and are the major precursor of energy for cows. Partitioning DM and carbohydrates into fiber and nonfiber components provides a means of separating feeds into fractions that have distinct nutritional properties. Fiber can be defined nutritionally as the slowly digestible or indigestible fraction of feeds that occupies space in the gastrointestinal tract of animals. Of the current methods routinely used to determine fiber, only NDF measures total fiber and quantitatively determines differences between grasses and legumes, warm and cool season grasses, forages and concentrates, and roughages and energy feeds (66, 67). Biologically, NDF or its inverse, neutral detergent solubles, have been related to intake (73, 95), feed density (64), chewing activity (20, 106, 107), digestibility (82, 102), rate of digestion (94), and depression of digestibility associated with high levels of intake (65).

Numerous studies have shown the importance of an optimal ratio of forage to concentrate (**F:C**) on the productivity of dairy cows (63, 75, 105). Mertens (66, 70, 72) proposed that NDF can be a valuable tool for establishing the upper limit for the F:C of dairy rations, but any attempt to use a single method to formulate rations must be recognized as an incomplete first step. Formulation of rations based on NDF, although achieving one of the most important objectives of ration balancing, which is to define the upper limit for the F:C, does not account for the more subtle differences in fiber that are associated with the kinetics of digestion and passage or with physical characteristics. The physical characteristics of fiber become critical when attempting to define the lower limit for acceptable F:C in dairy rations. Neutral detergent fiber measures the chemical characteristics, but not the physical characteristics of fiber such as particle size and density. These physical characteristics can influence animal health, ruminal fermentation and utilization, animal metabolism, and milk fat production independently of the amount or composition of chemically measured NDF. Neutral detergent fiber can be used effectively to define the lower limits of the F:C when simple mixtures of long or coarsely chopped forages are mixed with low fiber concentrates to formulate rations. However, NDF is less effective in formulating rations when finely chopped forages or nonforage fiber sources are used.

The physical properties of dairy rations are affected by the F:C ratio, types of forages and concentrates, proportion of ground nonforage fiber sources, and particle size and processing of ration ingredients. Balch (5) proposed the use of chewing time per kilogram of DM as a biological measure of the physical characteristics of forages, which he termed the fibrousness characteristic. Sudweeks et al. (95, 96) measured chewing time of a variety of forages and concentrates and developed the roughage value index system for meeting chewing requirements. The effects of fiber amount and source on milk fat production have been known for a long time (39, 101). Some nutritionists developed the concept of effective fiber or roughage replacement values for feeds that could be used quantitatively to formulate rations that would maintain the production of fat milk. These effective fiber values were based on different standards, such as cottonseed hulls (55), hay (47, 76), or alfalfa silage (29, 97). Mertens (69) suggested that the role of physical characteristics of feeds would be elucidated more clearly if the differences in chemical fiber (NDF) among feeds were removed. He suggested a system for assessing the roughage value of feeds based on a theoretical standard (long grass hay containing 100% NDF). Mertens (69) standardized the effectiveness values that had been proposed previously (29, 55, 97) so that they would be on the long grass standard scale and used those values as roughage value adjustment factors that could be multiplied times NDF (72).

The objectives of this research were 1) to define the physiological responses of dairy cows to effective fiber, 2) to develop a system for assessing the effective fiber values of feeds, and 3) to establish a framework for quantifying the effective fiber requirements of dairy cows.

PHYSIOLOGICAL RESPONSES TO EFFECTIVE FIBER

Differences in the amount and physical properties of fiber can affect the utilization of the diet and the performance of the animal. When too much fiber is included in the ration, energy density is low, intake is reduced, and productivity is decreased. When too little fiber is included in the ration, a variety of symptoms can occur, ranging from altered fermentation in the rumen to severe acidosis resulting in death. Although severe acute lactic acidosis can have dire consequences, the effects of altered fermentation and mild or borderline acidosis (which affects ruminal digestive efficiency, intake and metabolism, milk fat production, and the long-term health of the animal) may have the greatest economic impact on dairy production.

Increased amounts of fiber in dairy rations stimulate chewing activity and reduce acid production. The cascade of events leading to a decrease in animal performance when too little effective fiber is fed includes decreased chewing activity, leading to less salivary buffer secretion, which leads to lower ruminal pH and results in altered ruminal fermentation patterns and the low ratios of acetate to propionate (**A:P**) that ultimately result in modified animal metabolism and reduced milk fat synthesis. It can be argued that inadequate fiber in the ration may not be the primary cause of the foregoing scenario. In many situations, readily fermentable nonfibrous carbohydrates (**NFC**) or nonstructural (**NSC**) carbohydrates are used to replace fiber in low fiber rations, and these rapidly fermenting carbohydrates may contribute to animal responses to low fiber rations.

It is important to maintain a distinction between NFC (71), which is calculated by difference (NFC = 100 – NDF – CP – ether extract – ash), and NSC or total nonstructural carbohydrates (**TNC**), which are measured by analytical methods (93). Mertens (71) reported that the values of NFC and NSC or TNC are not equal for many feeds; therefore, the terms are not synonymous and should not be used interchangeably. The primary, but not the only, difference between NFC and NSC is pectin, which is included in NFC, but not in NSC, which is determined analytically as starch and sugars.

It can be hypothesized that lower ruminal pH and altered fermentation patterns are the result of too much NFC or NSC rather than too little fiber; therefore, rations should be balanced for NFC or NSC rather than for NDF. This theory is plausible when problems occur because concentrates are substituted for forages in dairy rations. In this situation, there is a nearly perfect inverse correlation between NDF and NFC or NSC, and which of these decreases animal performance cannot be resolved. However, some situations (50, 51, 95, 110, 111) indicate that lack of effective fiber is the primary cause of borderline acidosis and milk fat depression. Observations that ruminal fermentation is altered and milk fat percentage is depressed when the forage in rations is finely ground or chopped, but without changes in the F:C ratio and the concentrations of NFC or NSC in the ration indicate that the effectiveness of fiber rather than the substitution of NFC for NDF is the primary cause of problems in diets with low fiber. This observation also suggests that, in addition to the chemical nature of carbohydrates (NDF or NFC), the physical characteristics of fiber are critical for the optimal function of the rumen.

Both the amount and effectiveness of fiber can affect ruminal fermentation and animal metabolism, resulting in low milk fat production. Although the measurement of fiber is routine, the effectiveness of fiber has been defined in several ways. Traditionally, definitions have referred to the ability of fiber to maintain milk fat production and animal health “effectively”. To clarify the concepts being determined and discussed in this paper, physically effective NDF (**peNDF**) is distinguished from effective NDF (**eNDF**) on the basis of the following definitions. The peNDF is related to physical characteristics of fiber (primarily particle size) that influence chewing activity and the biphasic nature of ruminal contents (floating mat of large particles on a pool of liquid and small particles). The eNDF is related to the sum total ability of a feed to replace forage or roughage in a ration so that the percentage of fat in milk produced by cows eating the ration is effectively maintained. Because peNDF relates only to the physical properties of fiber, peNDF is a more restricted term and concept than eNDF.

Distinctly defining peNDF and eNDF helps to clarify the animal response that is used to assess the effectiveness of fiber and establishes a clearer basis for relating the new system to previous concepts and data. The animal response associated with peNDF is chewing activity. The peNDF of a feed is the product of its NDF concentration and its physical effectiveness factor (**pef**). By definition, pef varies from 0, when NDF is not effective in stimulating chewing activity, to 1, when NDF is fully effective in promoting chewing. Because peNDF is related to fiber concentration, particle size, and particle size reduction, peNDF is related to the formation of the ruminal mat, which may be a critical factor for selectively retaining fiber in the rumen, determining the dynamics of ruminal fermentation and passage, and stimulating rumination. The peNDF is related to animal health and milk fat depression because ruminal pH and the pattern of fermentation may both be a function of the production of salivary buffers during eating and rumination. Both eating and ruminating increase saliva production above baseline secretion (24), although the amount and composition of saliva may vary with chewing activity.

Conceptually, peNDF is related to fibrosity characteristic (5), roughage value index (95, 96), physical structure (80), and fibrosity index (91). However, peNDF differs from those concepts in that the feed attribute (peNDF) is based on NDF concentration and the relative effectiveness of the NDF in promoting chewing activity rather than being expressed as minutes of chewing activity per kilogram of DM per se. Chewing activity per kilogram of DM is an attribute of a feed that varies with the breed (108), size (4), and level of intake (91) of the animal to which it is fed and varies also with the fiber content and the particle size of the feed (58, 69). The peNDF provides a more consistent measure of physical effectiveness than chewing activity per kilogram of DM because peNDF is based on the two fundamental properties of feeds that affect chewing (NDF and particle size) and because variations from animal size and intake are minimized (pef are pure fractions in which the animal effects in the numerator and denominator cancel). Because peNDF values are constants for a feed and are additive in a feed formulation system, variation associated with animals is attributed to differences in requirements for peNDF and not arbitrarily partitioned between feed attributes and animal requirements.

The animal response that is associated with eNDF is milk fat percentage (i.e., the extent of milk fat depression associated with a feed). Thus, eNDF is related most closely to the previously proposed concept of effective fiber (47, 55, 76) that was used to maintain milk fat percentages when rations were formulated for dairy cows. By definition, effectiveness factors for NDF can vary from 0, when a feed has no ability to maintain milk fat percentage, to values greater than 1.0, when a feed maintains milk fat percentage more effectively than it maintains chewing activity. Logically, peNDF and eNDF should be highly correlated, especially for feeds that differ only in particle size. However, eNDF can be greater than peNDF for feeds that maintain milk fat percentage but do not stimulate chewing activity to a similar extent (e.g., feeds containing fats or intrinsic buffering capacity). Conversely, eNDF can be less than peNDF for feeds that detrimentally affect ruminal fermentation and milk fat production without affecting chewing activity (e.g., feeds containing sugars). Nonfiber attributes of feeds that influence milk fat synthesis are included in eNDF, but not peNDF.

Effective NDF is intended to take into account factors that affect peNDF, factors that affect ruminal acid production, and metabolic shifts that affect milk fat production. Thus, eNDF is related to intrinsic pH buffering and neutralizing capacity, fat concentration and composition, acid production during fermentation, pH changes reflecting the balance of buffering capacity and acid production, shifts in VFA amounts and ratios produced, and metabolic changes that influence the secretion of milk fat. Assuming that eNDF can be assessed by changes in milk fat percentage as the result of replacing forage with a test feed, eNDF also reflects the effects that substitution of fiber for readily fermentable carbohydrate and fat in the diet may have on milk fat production. Essentially, eNDF represents the total replacement value of a feed for an equivalent of amount of NDF from forage in its ability to maintain milk fat production. Because eNDF includes the effects of peNDF and additional factors that help maintain milk fat percentage, the effectiveness factor for NDF would be expected to be larger than the pef for most feeds. In addition, factors such as stage of lactation, body condition, and level of production may result in insensitivity of milk fat depression to dietary changes. Although there are no data comparing the relative efficacy of chewing activity and milk fat depression as indicators of metabolic disorders, it is a common field observation that lameness can be observed in herds with no apparent milk fat depression. The larger coefficients for eNDF than for peNDF and the occasional insensitivity of milk fat concentration to dietary changes suggest that eNDF may be a less sensitive indicator than peNDF of the effectiveness of fiber in preventing intake depression, borderline acidosis, lameness, or displaced abomasum in dairy cows.

ASSESSING THE EFFECTIVENESS OF FIBER IN FEEDS

To improve the current approach for meeting the fiber requirements for dairy cows (77), a new system must be based on feed characteristics that can be defined and, preferably, be determined quantitatively using routine laboratory methods. The system should also be based on animal requirements, which vary with the feeding situation, diet composition, and animal attributes. Fiber effectiveness, because it is a nutritional concept, can only be measured by using animals. Laboratory assessment of fiber effectiveness involves compromises, but these compromises are inconsequential if feed values and animal requirements are consistent with one another within the system of application. To simplify the mathematics of ration formulation and to be consistent with the NRC (77) requirements for other nutrients, it is desirable that the effective fiber values used in the new system be additive. Although requirements can be established first and feed values then developed to match those requirements, it seems most direct to determine effective NDF values for feeds and then use them to establish requirements that obtain the desired responses of the animal.

By definition, effectiveness must be related to fiber, although the scale on which it is based can be chosen arbitrarily. The biological assessment of peNDF and eNDF is different because physical effectiveness is narrowly defined in terms of chewing activity, whereas effectiveness is more inclusive and is defined to represent all properties of the feed that help to maintain milk fat percentage. By relating both physical effectiveness and effectiveness to NDF, the proposed system can use laboratory measurements to assess more accurately the effective fiber of the specific feeds used by a particular dairy operation.

Several researchers (5, 34, 95, 107) have demonstrated that chewing activity is a characteristic that reflects the chemical and physical properties of feeds (NDF, particle size, intrinsic fragility, and moisture). Chewing activity (the sum of eating and ruminating time) is also a function of the type, size or age, and DMI of the animal and perhaps measurement technique. What is less clear is how chewing activity can be used to assign values to feeds in a unified, quantitative system.

Biological Assessment of Fiber Effectiveness

The first step in developing a common scale for assessing physical effectiveness is to define a reference against which all feeds are compared. Mertens (69) proposed that feeds be compared against a hypothetical standard that would result in the maximum amount of chewing per kilogram of DM or NDF. He suggested that the reference feed should be a long grass hay containing 100% NDF that is assigned a pef of 1.0, resulting in a peNDF of 100 for the hypothetical standard. Mertens (69) estimated that the long grass hay reference standard would result in about 240 min of chewing per kilogram of DM or NDF for nonlactating dairy cows eating 0.4 to 2.0 times maintenance. Although the variation in chewing among long forages is related primarily to differences in NDF concentration, chewing per kilogram of NDF increased as the NDF in long forages increased (Table 1). Regression of NDF percentage versus total chewing activity per kilogram of DM (minutes per kilogram of DM = –97.1 + 3.10[%NDF], $r^2 = 0.95$) or per kilogram of NDF (minutes per kilogram of NDF = 1.5 + 2.37[%NDF], $r^2 = 0.88$) followed by solving these

TABLE 1. Relationship of chewing activity (eating and ruminating) per kilogram of DM or NDF to the NDF concentration in long hays fed to cows.

Feed	Crude fiber	NDF[1]	Total chewing activity		Reference
	(% of DM)		(min/kg of DM)	(min/kg of NDF)	
Dried ryegrass	18.6	48	53	111	Freer and Campling (45)
Alfalfa	28.4	49	61	125	Sudweeks et al. (96)
Dried grass	21.4	51	63	123	Campling and Freer (22)
Ryegrass	31.5	65	90	139	Freer and Campling (45)
Grass	31.1	65	103	158	Freer et al. (46)
Ryegrass	33.2	68	104	152	Freer and Campling (45)
Grass	31.1	65	107	165	Freer et al. (46)
Oat straw	40.6	78	163	209	Freer et al. (46)
Oat straw	41.2	79	143	181	Freer and Campling (45)
Oat straw	44.7	84	164	195	Campling and Freer (22)

[1]NDF calculated from crude fiber concentration (67).

equations for a long forage containing 100% NDF gave chewing activities of 213 or 238 min/kg of NDF, respectively. When differences in intake were removed using covariance, chewing activity at the average intake of 1.1 times maintenance was 204 or 232 min/kg of NDF, respectively, using chewing activity per kilogram of DM or NDF as the dependent variable.

Particle size reduction decreased chewing activity per kilogram of NDF (Table 2). Chopping forages through screens with 40-mm openings reduced total chewing activity to 80% of the unchopped original material. Grinding forages can reduce chewing activity to 20 to 60% of that for long forage, and chopping forages to a theoretical length of cut of about 5 mm resulted in about 70% of the chewing of forages chopped to a theoretical length of cut of 20 mm (Table 2). Mertens (69) assumed an exponential relationship between theoretical length of cut and chewing activity and predicted that the chewing activity of forages with theoretical lengths of cut of 40, 20, 5, and 1 mm would be 80, 70, 50, and 25%, respectively, of that for long forage.

The conclusions of Mertens (69) were based on a small number of observations using dairy cows that consumed diets containing mostly low quality forage during the late lactation or during the nonlactating period. To develop the relationships between NDF, physical form of the NDF, and chewing activities of high producing dairy cows consuming concentrates and nonforage fiber sources, data from 45 experiments in which chewing activities were measured (274 combinations of cows and treatments) were compiled from the literature (7, 8, 9, 10, 11, 12, 13, 14, 16, 21, 22, 25, 26, 28, 29, 30, 33, 35, 36, 37, 43, 44, 45, 46, 49, 50, 51, 52, 53, 54, 59, 60, 62, 78, 79, 85, 88, 92, 96, 97, 98, 104, 110, 111, 112). The NDF concentration of forages and concentrates were estimated in 108 combinations from early experiments in which crude fiber, but not NDF, was measured. The tables of Mertens (72) and equations of Mertens (67), Sauvant et al. (90), and D. R. Mertens (1995, unpublished) were used to estimate NDF from acid detergent or crude fiber. To be consistent and to minimize possible confounding of the relationship between NDF and physical effectiveness caused by variability in the methods that were used to measure NDF, calculated values (adjusted to correspond to reported feed qualities) were used to determine the NDF from forage and nonforage sources for the remaining experiments. The NDF of complete diets reported for the remaining 166 combinations averaged 0.9 percentage units higher than calculated values. In most instances, researchers did not determine NDF using α-amylase treatment, and the difference between reported and calculated concentrations probably reflects this difference in the method for determining NDF.

A physical form classification scheme was designed to conform to the information on quantitative particle size provided by various researchers (Table 3). The appropriateness of this system was confirmed by the logical pattern of chewing activities across classes and the consistency of chewing activities for NDF intake within classes. Feeds were assigned to a physical form class based on the description of the feeds provided. If no particle size information was provided, feeds were assigned to the median class for that feed source.

Multiple regression was used to derive initial estimates of pef for 25 NDF sources (long, chopped, dried, or ground grass hay; coarsely, medium, or finely chopped grass silage; coarsely, medium, or finely chopped corn silage; long, coarsely, medium, or finely chopped or ground alfalfa hay; coarsely,

TABLE 2. The effect of particle size of forages on the chewing activity of cows.

Feed and physical form	NDF	Total chewing activity			Reference
	(% of DM)	(min/kg of DM)	(min/kg of NDF)	(% reduction)	
Alfalfa hay					
Long	54	72	134	100	D. R. Mertens, 1995, unpublished
Chopped (3.8 cm)[1]	54	59	109	82	
Bermudagrass hay					
Long	72	108	149	100	D. R. Mertens, 1995, unpublished
Chopped (3.8 cm)	72	85	118	79	
Alfalfa hay					
Long	53	62	117	100	Sudweeks et al. (96)
Chopped (3.8 cm)	53	44	84	72	
Oat straw					
Long	84[2]	163	194	100	Campling and Freer (22)
Ground	75[2]	84	113	58	
Ryegrass					
Long	65[2]	90	139	100	Freer and Campling (45)
Finely ground (1.2 mm)	64[2]	19	29	21	
Corn silage					
1.9 cm TLC[3]	68	66	97	100	Sudweeks et al. (96)
1.3 cm TLC	62	60	96	99	
0.6 cm TLC	60	40	66	68	
Alfalfa hay					
2.5 cm TLC	55	52	95	100	Santini et al. (88)
0.5 cm TLC	45	30	66	69	

[1]Screen aperture diameter.

[2]NDF calculated from crude fiber concentration (67).

[3]Theoretical length of cut.

medium, or finely chopped alfalfa silage; nonforage fiber sources; or concentrates consisting primarily of rolled barley, rolled high moisture corn, cracked or coarsely ground corn, medium-ground corn, ground complex mixtures, or pelleted complex mixtures). A zero-intercept model was used under the assumption that no chewing activity would occur if no feed was consumed. Minutes of chewing per day were regressed against NDF intake for each source fed in each cow and treatment combination. Regression coefficients in these equations represent the minutes of chewing activity per kilogram of NDF for each source and physical form. Long grass hay was used as the standard for calculating the pef for all other NDF sources

TABLE 3. Relationship between the physical form classification system used to describe feeds and the descriptions used in published experiments.

Classification	TLC[1]	Screen aperture[2]	Grass hay	Grass silage	Corn silage	Alfalfa hay	Alfalfa silage	Concentrates
	(cm)							
Long			Long					
Coarsely chopped	4.8 to 8.0		Coarse	Coarse		Long		
Medium-coarse chopped	2.4 to 4.0		Medium	Medium	Coarse	Coarse		
Medium chopped	1.2 to 2.0		Fine	Fine	Medium	Medium	Coarse	
Medium-finely chopped	0.6 to 1.0				Fine	Fine	Medium	
Finely chopped	0.3 to 0.5						Fine	
Ground or pelleted	0.15 to 0.25		Ground Pelleted			Ground Pelleted		
Rolled								B, HMC[3]
Coarsely ground or cracked		1.25						Cr. Corn
Medium ground		0.90						C, Complex
Finely ground or pelleted		0.63						Pelleted

[1]Theoretical length of cut.

[2]Grinder screen aperture.

[3]B = Barley, HMC = high moisture corn (both shelled and ear corn) that is coarsely rolled or cracked, Cr. corn = coarsely cracked shelled corn, C = ground corn, and Complex = ground mixtures of fibrous protein supplements and nonforage fiber sources.

by dividing the regression coefficient for each source by the regression coefficient for long grass hay.

The independent variable matrix in the data file is sparse and contains numerous 0 values because only a limited number of NDF sources and physical forms were fed in a given experiment. To detect differences in methodology among citation sources that might bias results, the average residual deviations for each citation was determined, and the 7 citations (representing 27 combinations of cows and treatments) with the largest deviations (>180 min of chewing/d) were removed. The remaining 247 combinations were used to derive regression coefficients that were used to predict observations for all combinations, including the 27 combinations that were removed initially. Any observation that had a residual, or a ratio of predicted divided by observed, that was more than two times the root mean square of regression was considered to be an outlier for remaining analysis. This approach resulted in 18 combinations being identified as outliers.

Regression analysis estimated that the mean chewing time for long grass hay was 150 min/kg of NDF. The pef were estimated by dividing observed total chewing time by 150 min/kg of NDF and regressing this variable versus the kilograms of NDF intake from each NDF source and physical form. Regression coefficients from this analysis are an estimate of the pef for the NDF from each source. Many of the pef for NDF were estimated accurately by regression with standard errors that were 0.05 or less (Table 4); however, there were inconsistencies in the pattern of pef within and among NDF sources. Regression estimates of pef for concentrates had large standard errors, suggesting that the feed classes defined in Table 3 may have been too broad. Future research should focus on partitioning concentrates into ingredient types that have similar NDF and particle size distributions. Similarly, regression estimates of pef for ground and pelleted grass or alfalfa hay were large, indicating that more accurate classification by the size of grinder screen or pellet die might be beneficial. The pattern of regression estimates of pef with changes in physical form also was not consistent. For example, coarsely chopped grass or corn silage had larger pef than unchopped long hay and, in the case of corn silage, the regression estimates of pef did not decrease with the length of chop. To rectify some of these inconsistencies, pef were smoothed within an NDF source to obtain a logical progression of factors in relation to physical form. In addition, pef were standardized to provide the same factor for each physical classification described in Table 3.

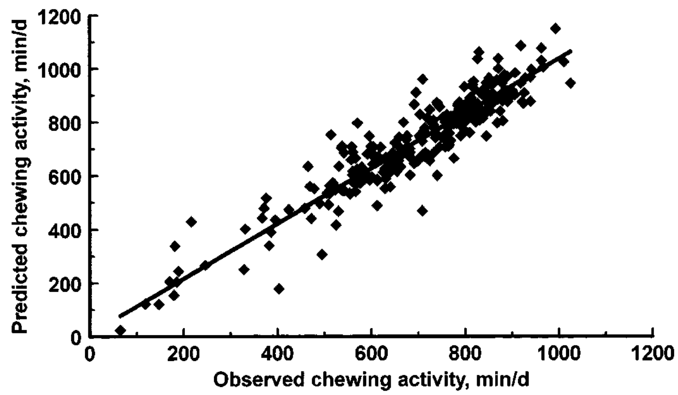

Figure 1. The relationship of chewing time predicted using standardized physically effective neutral detergent fiber values (♦) compared with observed values (line indicates the 1:1 relationship).

Standardized pef were used to identify potential outliers in a second cycle of statistical analysis. Nine combinations of cows and treatments were outliers in both the first and second screening. The remaining 265 combinations were used to evaluate the accuracy of the three sets of pef (Table 4). The r^2 of predicted versus observed daily total chewing activity for all data ranged from 0.54 using regression estimates of pef to 0.47 using standardized pef (Figure 1). Although these r^2 seem low, 1) they included the 9 outliers that were eliminated from multiple regression; 2) NDF and physical form classification were often estimated; 3) the database contained observations on lactating and nonlactating cows, restricted and ad libitum feeding, and separate and total mixed rations; 4) different methods were used for measuring chewing activity and adjusting it for times when animals were not observed during milking and for differences in intake on the day of measurement; and 5) comparisons were made across experiments that used different feeds, feeding systems, facilities, and animals. These last three factors represented a major source of variation. When outliers were removed and citation source was included in the model as a class variable, r^2 were greater than 0.76 for all estimates of pef (Table 4).

Regression analysis indicated that long grass hay required only 150 min of chewing per kilogram of peNDF, which was significantly lower than the hypothetical upper limit of 200 to 230 min of chewing per kilogram of NDF for the long grass hay reference standard derived from the data in Table 1. This difference in chewing time for long grass hay was apparently related to differences in intake. The regression of minutes of chewing per kilogram of standardized peNDF versus DMI was significant (chewing/kilogram of peNDF = 248.0 – 5.09(kilogram of DMI); $r^2 = 0.75$; SE = 15.2) when the citation effect was included in the model. Using this equation and the mean intake of the cows in the experiments listed in Table 1 (8.4 kg) resulted in an estimated 205 min of chewing per kilogram of long forage, which agrees with the regression using only data in Table 1. The cows in the data file for chewing activity averaged 17.6 kg of DMI, resulting in an estimate of 158 min of chewing per kilogram of peNDF.

Norgaard (80) proposed a system for assessing the physical structure of feeds for dairy cows that is based on chewing time and is related to the type of feed and

TABLE 4. Physical effectiveness factors (pef) for NDF in feeds of each physical form classification based on total chewing activity in relation to that elicited by long grass hay.

Feed and physical form	Regression[1]		Smoothed[2]	Standardized[3]
	pef[4]	SER[5]	pef	pef
Grass hay				
Long	1.00	0.03	1.00	1.00
Coarsely chopped	0.72	0.06	0.95	0.95
Medium chopped			0.90	0.90
Dried	0.80	0.08	0.80	0.80
Ground or pelleted	0.24	0.05	0.40	0.40
Grass silage				
Coarsely chopped	1.04	0.05	1.00	0.95
Medium chopped	0.96	0.03	0.95	0.90
Finely chopped	0.90	0.05	0.90	0.85
Corn silage				
Coarsely chopped	1.09	0.13	1.00	0.90
Medium chopped	0.93	0.03	0.95	0.85
Finely chopped	0.93	0.05	0.90	0.80
Alfalfa hay				
Long	0.82	0.03	0.85	0.95
Coarsely chopped	0.77	0.05	0.80	0.90
Medium chopped	0.72	0.06	0.75	0.85
Finely chopped	0.60	0.06	0.60	0.70
Ground or pelleted	0.54	0.08	0.40	0.40
Alfalfa silage				
Coarsely chopped	0.87	0.08	0.85	0.85
Medium chopped	0.81	0.03	0.80	0.80
Finely chopped	0.75	0.05	0.75	0.70
Nonforage fiber sources	0.25	0.14	0.30	0.40
Barley diets				
Rolled	0.69	0.06	0.70	0.70
High moisture corn				
Rolled	0.80	0.11	0.80	0.80
Corn diets				
Coarsely ground, rolled	0.94	0.38	0.50	0.60
Medium ground	0.40	0.09	0.30	0.40
Complex mixtures				
Ground	0.22	0.08	0.30	0.40
Pelleted	0.77	0.10	0.25	0.30
Prediction statistics				
All data (n = 274)				
r^2 (mean corrected)	0.54		0.50	0.47
SER for pef	0.14		0.14	0.15
Outliers and between-experiment variation removed (n = 265)				
r^2 (mean corrected)	0.81		0.76	0.76
SER for pef	0.09		0.10	0.10

[1]Physical effectiveness factor for NDF determined by regression.

[2]Physical effectiveness factor for NDF smoothed within feed source to obtain a logical progression among physical forms.

[3]Physical effectiveness factor for NDF standardized to provide a logical progression across feed sources and physical forms.

[4]Physical effectiveness factor for NDF.

[5]Standard error of the regression coefficient estimate of pef.

TABLE 5. Estimates of standard chewing times of feeds for dairy cows according to the physical structure evaluation system (80).

	Degree of comminution		Degree of chopping		
Characteristic	Finely ground	Coarsely ground	Fine (F^1 = 0.25)	Coarse (F = 0.75)	None or slight (F = 1.00)
Physical structure group	1	1	2	2	2
Typical feedstuffs	Concentrates and molasses	Rolled barley, dried grass, and cobs	Beet pulp	Finely chopped grass silage	Long hay Long straw Fresh grass Beets
Mean size of particles, mm	<1	1–5	5–10	10–50	>50
Standard chewing time, min/kg of DM	4	10	Calculated[2]	Calculated	Calculated

[1]Weighting factor for the effect of chopping.

[2]Standard chewing time = F × 3 × percentage of crude fiber, assuming 300 min of chewing/kg of crude fiber for noncomminuted feeds.

its degree of grinding or chopping. The system of Norgaard (80) assigns to feeds a chewing time that is based on physical classification and crude fiber (Table 5). Feeds in physical structure group 1 (grains, concentrates, and pelleted feeds) are given a standard chewing time of 4 or 10 min/kg of DM, depending on their particle size. Feeds in physical structure group 2 (forages and nonforage fiber sources) are given a chewing time based on a standard chewing time of 300 min/kg of crude fiber intake for unchopped feeds multiplied by a comminution factor. Sauvant et al. (91) observed a similar relationship between crude fiber and chewing activity. Although fibrosity index (minutes of total chewing per kilogram of DM) varied widely among feeds, Sauvant et al. (91) concluded that fibrosity index is not an additive feed unit and only provided an indication of ration adequacy. Part of the inaccuracy of the physical structure and fibrosity index systems may be related to the use of crude fiber, which is not as good an indicator of total fibrousness of feeds as is NDF, and to the limited number of comminution factors. However, the major limitation of these systems may be related to the use of chewing time as a feed attribute. The variability of chewing time per kilogram of DM that is associated with animal characteristics, especially DMI, limits its usefulness as a feed attribute that can be used in systems of linear equations to formulate diets.

The pef in Table 4 are similar to the degree of chopping factor in the system proposed by Norgaard (80). The difference in the two systems is that this proposed system is based on peNDF and eNDF, but the system of Norgaard (80) is based on chewing activity per se (Table 5). However, the pef in Table 4 can be used to estimate the minutes of total chewing time per kilogram of DM. The quadratic effect of NDF intake and the interaction between NDF intake and DMI on regression estimates of pef were tested and found to be nonsignificant. Thus, the expected chewing activity per kilogram of feed can be calculated as 150 × 0.01 × peNDF for lactating cows consuming about 18 kg of DM/d. A ground concentrate containing 12% NDF with a pef of 0.4 (Table 4) would result in a total chewing time of 7.2 min/kg of DM, which is greater than the standard value given by Norgaard (80) for finely ground concentrates of 4 min/kg of DM. Similarly, a NDF of 20% and a physical effectiveness value of 0.7 for rolled barley estimates total chewing time to be 21 min/kg of DM in the proposed system compared with 10 min/kg for the system of Norgaard (80). The longer chewing times estimated by the factors in Table 4 may be related to the longer eating times associated with total mixed rations and ad libitum feeding than with meal feeding. Partitioning some of the daily rumination time to the NDF in concentrates when using regression analysis may also be a contributing factor.

Accurate assignment of eNDF values to feeds is more difficult than determining peNDF values because eNDF is a more inclusive characteristic and is therefore subject to greater variation from differences in animals, experimental conditions, and feed ingredients. However, Armentano and Pereira (3) presented a system to assess biologically the eNDF values of forages and nonforage fiber sources using a standard curve and linear regression in which milk fat percentage was the response variable. In several experiments, Clark and Armentano (29) and Swain and Armentano (97) measured responses of both chewing and milk fat percentage to the replacement of alfalfa silage NDF with NDF from nonforage fiber sources. Similar to peNDF, the assignment of eNDF values to feeds needs a common reference so that all feeds are expressed on the same basis. The values for pef in Table 4 suggest that the alfalfa silages used by those researchers (29, 97) probably had an effectiveness of <1 compared with that of long grass hay. Thus, their (29, 97) effectiveness factors may underestimate the value of the nonforage fiber sources to replace the long grass hay reference standard.

A subset of the chewing activity data (219 combinations of cows and treatments) was used to determine effectiveness factors for NDF using multiple regression. Milk fat percentage was regressed on the intake of NDF from each of the 25 sources and physical forms. The resulting regression coefficients represent the change in milk fat percentage per kilogram of NDF intake. Similar to the slope ratio technique proposed by Swain and Armentano (97), the ratio of the regression coefficient for each NDF source and physical form to the regression coefficient for long grass hay provides an estimate of the effectiveness factor. However, multiple regression failed to derive realistic estimates for the effectiveness factors. All regression coefficients for concentrate feeds were negative, which suggested that consuming NDF from these sources would decrease milk fat percentage. The confounding of sources and concentrations of concentrate NDF may be a problem in the data file because, in most experiments, only one concentrate source and level was fed.

Laboratory Assessment of Fiber Effectiveness

Chewing activity and alleviation of milk fat depression are good biological responses for providing a quantitative measure of fiber effectiveness. However, to be useful for site-specific situations, systems used to formulate rations must be based on a feed evaluation scheme that allows the effectiveness of a specific feed to be determined in the laboratory. One of the desirable consequences of using NDF as the basis for describing the effectiveness of feeds in stimulating chewing and milk fat production is that NDF allows the variability in the chemically determined fiber content of feeds to be taken into account. The peNDF of a specific feed can be determined by multiplying the appropriate pef (Table 4) times the measured NDF. The only caveat to this approach is related to the differences in NDF methods that are being used routinely.

The original NDF method used sodium sulfite, but not α-amylase (48, 103); the neutral detergent residue modification proposed by Robertson and Van Soest (86) contained α-amylase, but no sulfite; and the NDF method recommended by the National Forage Testing Association (100) used both α-amylase and sodium sulfite. Differences in NDF, neutral detergent residue, and NDF treated with α-amylase can be substantial, especially for animal products and sources of heated nonforage fiber (57). Although animal products do not contain plant cell walls, these products can contain fiber, which is defined nutritionally as the indigestible or slowly digestible fraction of feed that occupies space in the digestive tract (57). To measure accurately the fiber in concentrates and corn silage, treatment of NDF with α-amylase is needed (86). To measure the indigestible and slowly digestible fraction in heated nonforage fiber sources, both sulfite and α-amylase should be used (57). The only fiber method that can be used on all feeds is the method recommended by the National Forage Testing Association (100). Researchers should take care in describing the method they use and verifying that it conforms to the procedure cited.

Laboratory assessment of eNDF and peNDF for individual feeds or feeds that have not been assessed biologically also may be possible. Mertens (69) suggested that roughage value or effective fiber could be related to physical measurements of particle size combined with NDF analysis. This concept is based on the hypothesis that only the fiber in particles that are large enough to require chewing should be related to peNDF. To implement this system it is necessary to determine the particle sizes that are retained in the rumen and stimulate chewing or to determine particle sizes that escape the rumen and do not stimulate chewing even though they contain fiber. The rate of escape of particles can be used to indicate the particles sizes that are retained in the rumen. Dixon and Milligan (38) reported that particles retained on sieves with apertures of 6.8, 4.9, 3.2, 2.0, 0.7, and 0.25 mm had rates of passage of 0.0004, 0.010, 0.025, 0.041, 0.048, and 0.059/h, which suggested that particles retained on sieves with apertures of 3.2 mm and larger passed out of the rumen slowly and required additional chewing. Particles that appear in feces have escaped the rumen and can be used to indicate the size of particles that do not need or stimulate chewing. Poppi et al. (84) concluded that particles retained on a 1.18-mm sieve have a high resistance to passage from the rumen of both cattle and sheep. Cardoza (23) measured the particle size of feces from dairy cows fed 40 different combinations of forage and concentrate. He (23) observed that <5% of fecal particles were retained on sieves with 3.35-mm apertures and that the median particle size of feces for dairy cows was retained on sieves with apertures of 0.4 to 1.2 mm. This observation suggests that particles

TABLE 6. Particle size distributions of nonforage fiber sources and concentrate feeds using vertical shaking.

Feed	n	Medium size	<0.3 mm	>1.18 mm	>3.35 mm
		(mm)	(% of air-dried sample)		
Barley, crimped	1	3.24	0.0	98.9	48.8
Oats, rolled	1	1.81	6.2	76.5	36.7
Citrus, unground	1	2.59	2.8	76.0	47.4
Corn cobs, ground	1	1.23	8.3	55.7	12.6
Corn, ground	2	1.00	10.6	47.6	3.2
Corn gluten feed	6	0.96	9.0	36.2	3.0
Barley, ground	1	0.73	14.3	33.6	0.0
Wheat bran	2	0.86	9.8	33.3	0.0
Soybean meal	10	0.75	10.0	22.9	0.0
Brewers grains	5	0.69	11.6	17.6	0.0
Peanut hulls, ground	4	0.59	18.4	12.3	0.1
Hominy	3	0.72	3.3	9.0	0.0
Sunflower meal	1	0.46	27.3	9.0	0.0
Meat meal	1	0.77	0.4	7.7	0.0
Alfalfa, dehydrated	3	0.31	49.9	5.6	0.0
Canola or rapeseed meal	3	0.47	23.7	4.8	0.0
Distillers dried grains	4	0.49	20.4	4.1	0.0
Soybean hulls, ground	9	0.45	24.4	2.9	0.0
Wheat middlings	5	0.39	29.8	1.8	0.1
Rice mill feed	1	0.36	32.2	0.5	0.0

passing through a 1.2-mm aperture readily pass out of the rumen and provide little stimulus for chewing, which is in agreement with the conclusions of Poppi et al. (84).

A simple system for estimating peNDF from chemical and physical measurements in the laboratory can be based on NDF concentration and the proportion of particles that are retained on a 1.18-mm sieve. Mertens (68) measured the particle size distribution of several feeds (Table 6) that can be used to demonstrate this system. If it is assumed that pef are equal to the proportion of particles retained on a 1.18-mm sieve, peNDF can be estimated by multiplying NDF concentration by the proportion of particles retained on the sieve (Table 7). Santini et al. (88) proposed a similar system based on the intake of forages that were adjusted for particle length.

The proposed laboratory method for estimating peNDF is based on three assumptions: 1) that NDF is uniformly distributed over all particle sizes, 2) that chewing activity is equal for all particles retained on a 1.18-mm sieve, and 3) that fragility (ease of particle size reduction) is not different among sources of NDF. The first assumption could be overcome by directly analyzing the fiber content of the material retained on the 1.18-mm sieve and expressing it as peNDF concentration in total DM. The second assumption could be accounted for by using additional sieves (to keep the laboratory method simple, perhaps sieves with 3.35- and 1.18-mm apertures would suffice) to define the particle size distribution and relate specific chewing activities to each particle size. The relationship between particle size and chewing activity may be complex, but this simple system may account for the majority of the impact of variation in particle size on peNDF. The third assumption could be overcome by measuring the grinding energy (27, 109) that was required to reduce the particle size of the feed retained on a 1.18-mm sieve or relating fragility to the amount or composition of NDF.

The physical effectiveness of fiber is most likely related to a multitude of factors, including DMI, par-

TABLE 7. Estimating the peNDF of feeds using chemical and physical measurements in the laboratory (69).

Feed	NDF	1.18-mm sieve	peNDF[1]
	(% of DM)	(Fraction retained)[2]	(% of DM)
Standard	100	1.00	100.0
Grass hay	65	0.98	63.7
Legume hay	50	0.92	46.0
Legume silage, coarse chop	50	0.82	41.0
Legume silage, fine chop	50	0.67	33.5
Corn silage	51	0.81	41.5
Brewers grains	46	0.18	8.3
Corn, ground	9	0.48	4.3
Soybean meal	14	0.23	3.2
Soybean hulls	67	0.03	2.0
Rice mill feed	56	0.005	0.3

[1]peNDF is calculated by multiplying NDF by the fraction retained on a 1.18-mm sieve.

[2]Using vertical shaking.

ticle size, particle shape, fragility, moisture, type of preservation, and ratio of eating time to ruminating time. A laboratory system for estimating pef would be most accurate when a function was derived that would account for each of these variables. As intake increases, the amount of chewing per unit of DM decreases, probably because there is a maximum time that animals can chew in a day (approximately 1000 min/d, Figure 1). If measurements of particle size description in the laboratory can be related to grinder screen sizes or chopper theoretical lengths of cut in Table 4, interpolation of intermediate pef may be possible. Also, particle shape may affect physical effectiveness. Troelsen and Campbell (99) reported that legume particles in feces tended to be more cuboidal than grass particles. Mertens et al. (74) observed that the ratio of length to width of sieved material differed among sources, ranging from 3:1 in short alfalfa particles to 10:1 for long grass particles. Particle size separators that shook the sample vertically tended to separate particles by their minimum cross-sectional dimension rather than by length. If length of particles is important in chewing activity, then adjustment for the shape of particles may improve the ability to use laboratory measures to estimate peNDF.

In addition to the variables used to assess peNDF, laboratory methods for measuring effectiveness factors or eNDF may include factors related to 1) intrinsic pH buffering or neutralizing capacity, 2) ability to lower pH, 3) type and pattern of nutritive end products that are absorbed, and 4) rate and extent of fermentation associated with the substitution of slowly fermenting substrates for rapidly fermenting substrates. Many of these variables are interrelated, and the number of additional coefficients or measurements that are needed to predict eNDF from peNDF is unclear. Because they differ mainly in particle size and not greatly in chemical composition, the correlation between eNDF and peNDF for forages is expected to be high, and a simple regression equation could be used to predict eNDF from peNDF. This relationship may be different for grasses and legumes because intrinsic buffering capacities are different. The relationship between peNDF and eNDF for fibrous by-product feeds or nonforage fiber sources probably is more complex than that for forages.

If it is assumed that the rate of fermentation, types of end products, and pH changes are similar for NFC from different sources, a simple ratio of NFC in corn to NFC in the test feed could provide a method of partially accounting for the difference in overall fermentability among feeds relative to corn. A more accurate system may use the ratio of measured total ruminally fermentable organic matter in corn divided by that in the test feed. Perhaps a simple in vitro system for measuring fermentability, gas production, or pH change during fermentation could be used to convert peNDF to eNDF values. In vitro measurements would account for differences in feeds that are associated with variation in fat concentrations (because fats would not ferment to produce acid) and for differences in fibrous versus nonfibrous carbohydrates in feeds. However, these measurements would not account for differences in end products that are absorbed unless the variation in end products is correlated with pH or fermentability. Because the A:P and the amount of fat absorbed in the intestines can alter the amount of fat secreted in milk, these differences in feeds may need to be accounted for to convert peNDF to eNDF. This conversion may involve a simple regression equation using the fat concentration in feeds and a laboratory method designed to measure differences in A:P after fermentation.

Swain and Armentano (97) measured changes in chewing time and milk fat percentage when NDF in nonforage fiber sources was substituted for NDF in alfalfa silage. They also measured particle size distribution of the nonforage fiber sources. Their data allows the comparison of effectiveness factors. Rather than use the regression approach to assess pef, coefficients in Table 4 were used to determine the amount of chewing that was associated with concentrates, and the chewing that was associated with forages was determined by difference when no nonforage fiber sources was fed. Chewing activities for forage and concentrate were then used to determine the chewing times that were associated with each nonforage fiber source by difference (Table 8). Comparisons of effectiveness factors suggested that some relationship existed among them and that some of the factors already discussed may explain the differences. With the exception of corn gluten feed and brewers grains in trial 1, agreement was good ($r = 0.93$) between the laboratory assessment of physical effectiveness and that measured by chewing activities. With the exception of brewers grains in trial 1, effectiveness factors for maintaining milk fat percentage were larger than pef for stimulating chewing activity. With more data of this type, factors that relate the two effectiveness factors can be identified.

ESTABLISHING REQUIREMENTS FOR EFFECTIVE FIBER

Part of the difficulty in assigning fiber requirements is related to defining the response to be optimized. Fiber is needed in the diet of ruminants to

TABLE 8. Comparison of physical effectiveness factors (pef) and effectiveness factors (ef) of the NDF from various nonforage fiber sources using the data of Swain and Armentano (97).

Feed	NDR[1]	Lab pef[2]	pef[3]	ef[4]
Trial 1				
Corn gluten feed	35.5	0.09	0.63	0.71
Oat hulls	69.2	0.04	0.17	0.61
Brewers grains	59.7	0.24	0.80	0.25
Trial 2				
Corn gluten feed	33.1	0.04	0.04	0.40
Oat hulls	63.2	0.21	0.22	0.71
Brewers grains	56.3	0.24	0.32	0.46
Beet pulp	48.3	0.50	0.44	0.43
Malt sprouts	52.0	0.15	0.22	0.48

[1]Percentage neutral detergent residue determined using α-amylase and no sodium sulfite.

[2]Laboratory estimate of the physical effectiveness factor for NDF based on the proportion of DM retained on a 1.18-mm sieve.

[3]Physical effectiveness factor for NDF calculated from chewing activity relative to NDF in alfalfa silage.

[4]Effectiveness factor for NDF for maintaining milk fat percentage relative to NDF in alfalfa silage.

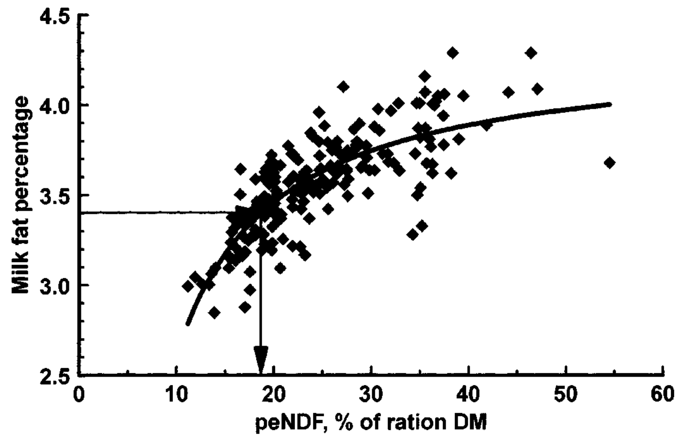

Figure 2. Relationship of physically effective neutral detergent fiber (peNDF) to observed milk fat percentage adjusted for citation effects (♦) showing reciprocal regression line [milk fat = 4.32 – 0.171(1/peNDF); r^2 = 0.63; SE = 0.17] and the peNDF concentration needed to obtain milk containing 3.4% fat.

prevent acute acidosis and death, founder, erosion of the ruminal lining, abscessed livers, milk fat depression, metabolic changes that induce fattening, borderline acidosis causing ruminal parakeratosis and chronic laminitis, altered ruminal fermentation, and reduced energy intake and FCM production. Maintaining milk fat percentage has been the focus of much of the research and field application of effective fiber because of its economic impact on the producer, the ease by which it can be measured, and the expectation that milk fat percentage is an acceptable reflection of animal well-being and performance. Certainly, animals do not perform optimally when milk fat is significantly depressed. However, low fiber in the diet possibly can detrimentally affect the animal without significant milk fat depression, which suggests that factors other than milk fat percentage, such as ruminal A:P, ruminal pH, or chewing activity may be useful in defining the fiber requirement of dairy cows.

Sudweeks et al. (96) proposed that rations should contain ingredients that result in approximately 30 min of chewing activity per kilogram of DM in order to maintain milk fat percentage. Norgaard (80) proposed the same requirement to maintain optimal ruminal function and milk fat percentage. However, the data of Woodford and Murphy (111) indicated that as little as 24 min of chewing activity per kilogram of DM were adequate to maintain milk fat percentage. To establish chewing and peNDF requirements for maintaining milk fat percentage, a database was compiled containing 213 combinations of cows and treatment from 36 citations (7, 8, 9, 10, 11, 12, 13, 14, 29, 30, 33, 35, 36, 37, 43, 44, 49, 50, 51, 52, 53, 54, 59, 60, 62, 78, 79, 85, 88, 92, 96, 97, 98, 110, 111, 112). Four combinations had residuals that were greater than three times the standard error of regression and were removed as outliers.

Two models were used to predict milk fat percentage from peNDF and chewing activity using the GLM procedure (89). A quadratic polynomial equation was evaluated, and, when the quadratic term was not significant ($P < 0.05$), this model was reduced to its linear form. In addition, the reciprocal of each independent variable was regressed against milk fat percentage (Figure 2). This hyperbolic model has two desirable characteristics: 1) the model obtains an asymptotic plateau in the dependent variable, and 2) the reciprocal transformation results in a linear form of the regression. The first characteristic is advantageous because the asymptotic model fits the biological constraint that milk fat percentage and ruminal pH do not increase indefinitely but achieve a plateau that is established by the physiological state and genetic potential of the animal. The linear form of the reciprocal transformation results in an intercept that estimates the asymptote, which is advantageous statistically. The asymptotic intercept of the reciprocal model is estimated more accurately because treatments are often included in experimental designs to obtain the maximum milk fat percentage for the experimental groups of cows. Conversely, the intercept of the polynomial equation is more difficult to estimate in most experiments because the experimental design often cannot guarantee that the lowest level of milk fat percentage is observed.

TABLE 9. Estimating the physically effective neutral detergent fiber (peNDF) required to maintain milk fat percentages of cows in early to midlactation.

Item	Milk fat percentage regressed on			
	Total chews		peNDF	
	(min/d of DM)	(min/kg of DM)	(kg/d of DM)	(% of DM)
Reciprocal regression				
Mean milk fat asymptote of all citations	3.92	3.97	4.12	4.32
Regression coefficient	–0.257	–0.142	–0.265	–0.171
Standard error regression	0.19	0.18	0.18	0.17
r^2 (variation among citations removed)	0.24	0.40	0.38	0.63
Polynomial regression				
Mean milk fat intercept of all citations	2.64	2.97	2.88	2.17
Linear regression coefficient	0.00129	0.0163	0.136	0.0796
Quadratic regression coefficient	NS[1]	NS	NS	–0.00085
Standard error of regression	0.18	0.19	0.18	0.17
r^2 (variation among citations removed)	0.50	0.55	0.42	0.70
Requirements for specified milk fat percentages				
3.6% Milk fat	744	36.1	5.01	24.0
SE[2]	36	1.1	0.20	0.5
3.4% Milk fat	589	27.7	4.01	19.7
SE	58	2.1	0.26	0.8
3.2% Milk fat	479	22.2	3.21	16.4
SE	87	3.1	0.63	1.0

[1]$P < 0.05$.

[2]SE = Standard errors for the requirements among the four methods of estimation. Standard errors within inverse regression estimates were approximately four times larger.

To remove the variation that was associated with experimental location, regression models included a class variable for the citation. For all dependent variables, the r^2 (after the variation among citations was removed) were lower for requirements expressed as amounts (kilogram of peNDF or minutes chewing per day) than for those expressed as proportions (kilogram of peNDF or minutes chewing per kilogram of DM), indicating that fiber requirements may be expressed more accurately as proportions in the diet. Quadratic functions of independent variables were not different ($P < 0.05$) from linear regressions except for peNDF as a percentage of DM. The higher r^2 of the linear regression than of the reciprocal regression suggested that milk fat percentage did not reach a plateau. However, this result may be an artifact of the interaction between data file characteristics and least squares fitting procedures. Milk fat percentages were not randomly or uniformly distributed across citations; therefore, least squares procedures partitioned variation to the citation effect in a way that maximized the linear response with dependent variables. The standard error of regression, which is a better estimate of regression accuracy than r^2, suggests that the reciprocal model estimates milk fat percentage with an accuracy that is equal to the polynomial model (ca 0.18), which agrees more closely with the biological expectation that milk fat percentage achieves a plateau as chewing activity or effective fiber increases.

Four estimates of the requirements for chewing activity or peNDF for milk fat percentages of 3.6, 3.4, and 3.2 (which differed by more than the standard error of regressions in Table 9) were calculated. The two regression models (reciprocal and polynomial) were used with two approaches. The reverse regression of X on Y was used to estimate the requirements for each characteristic and to provide an estimate of the standard deviation of requirements. However, reverse regression assumes that all error is associated with the X variable, that Y (milk fat percentage) is known exactly, and that X depends on Y. This relationship disagrees with the biological reality that milk fat percentage is a variable response to chewing activity or effective fiber and not a known input. A second approach was to use inverse regression (40) in which the regression of Y on X is solved for X using specified values of Y, and fiducial intervals for X are determined from the confidence limits of Y. The standard errors for requirements in Table 9 indicate the variation among the four methods of estimating requirements. The regression standard errors or inverse regression fiducial intervals for requirements within methods were about four times the standard error among methods. The observation that milk fat percentage is correlated with chewing activity and peNDF indicates that requirements must vary for different milk fat percentages. Standard errors confirm that requirements are different for 0.2-unit intervals of milk fat percentage. The NRC (77) provides no estimates of variation for other nutrient requirements that can be compared with these estimates to determine their relative accuracy.

To calculate requirements, the intercept of the regression model was the mean of all citation effects. To maintain milk fat at 3.6% would require 744 min of chewing/d or 36.1 min/kg of DM and 5.01 kg of peNDF/d or 24.0% of ration DM (Table 9). These requirements are more than the 30 min of chewing time per kilogram of DM that was recommended by Sudweeks et al. (96) and Norgaard (80) and the 21% roughage value (which is equivalent to or higher than peNDF values) that was recommended by Mertens (72). Most of the cows in the database were in early to midlactation when fat test is typically below the average for the entire lactation. Perhaps maintaining 3.4% milk fat during this stage of lactation would provide a better indication of the minimum requirements of dairy cows for chewing and peNDF. Formulation of rations to meet the peNDF concentration for maintaining 3.4% milk fat using forages, corn, and soybean meal results in rations that contain 25 to 27% NDF. Cows fed rations containing <25% NDF (<19% peNDF) often have depressed milk fat percentages, do not eat all the grain offered, and consume the coarse fiber in these rations (orts have lower NDF than the ration offered), suggesting that rations containing less than 25% NDF are deficient in fiber (D. R. Mertens, 1995, unpublished data).

Ruminal pH may be a better indication of ruminal health and optimal function than the maintenance of milk fat production, and Erdman (42) observed no relationship between ruminal pH and milk fat percentage. A database containing 114 observations from 26 citations was used to determine the effective fiber requirement for ruminal pH (1, 6, 7, 9, 10, 12, 14, 15, 17, 18, 19, 28, 31, 32, 33, 41, 44, 52, 56, 61, 62, 81, 87, 98, 111, 112). Experiments were restricted to those in which ruminal pH was measured a minimum of five times over at least an 8-h period after feeding. Most pH measurements in the database were the average of 15- or 24-h collection periods. The regression model included a class variable for the citation in which the experiment was reported, and the intercept of the regression model was the mean of all citation effects. The regression coefficients for the reciprocal and polynomial regressions and requirements for maintaining a ruminal pH of 6.0, 6.1, and 6.2 based on reverse and

TABLE 10. Estimating the physically effective neutral detergent fiber (peNDF) required to maintain a specified ruminal pH.

	Ruminal pH regressed on	
Item	peNDF	peNDF in ration
	kg/d	(% of DM)
Reciprocal regression		
Mean pH asymptote of all citations	6.50	6.67
Regression coefficient	–0.203	–0.143
Standard error of regression	0.11	0.10
r^2 (variation among citations removed)	0.48	0.71
Polynomial regression		
Mean pH intercept of all citations	5.66	5.50
Linear regression coefficient	0.0814	0.022
Quadratic regression coefficient	NS[1]	NS
Standard error of regression	0.11	0.09
r^2 (variation among citations removed)	0.49	0.81
peNDF required for a specified pH		
pH 6.2	6.32 (0.44)[2]	30.0 (1.2)
pH 6.1	5.25 (0.16)	25.6 (0.9)
pH 6.0	4.40 (0.28)	22.3 (0.7)
pH 5.9	3.66 (0.50)	19.3 (1.0)

[1]$P < 0.05$.

[2]Numbers in parentheses are the standard deviations of the requirements among the four methods of estimation. Standard errors within inverse regression estimates were approximately four times larger.

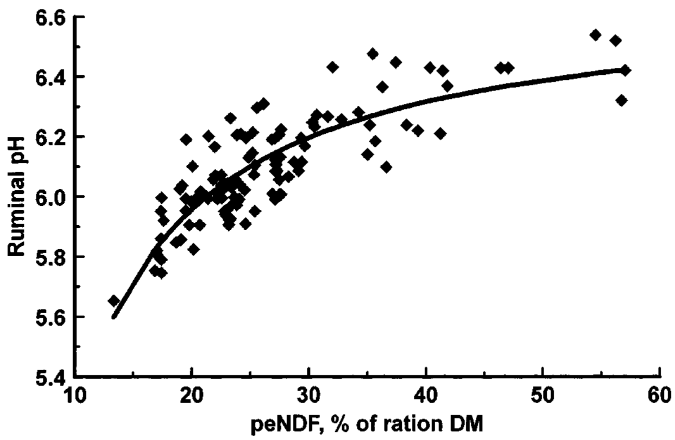

Figure 3. Relationship of observed ruminal pH adjusted for citation effects (♦) to physically effective neutral detergent fiber (peNDF) showing the reciprocal regression line [ruminal pH = 6.67 − 0.143(1/peNDF); r^2 = 0.71; SE = 0.10].

inverse regression are shown in Table 10. These equations suggest that a peNDF intake of 4.40 kg/d or a concentration of 22.3% of ration DM is needed to maintain a mean pH of 6.0.

Based on polynomial regression, the relationship between ruminal pH and peNDF was linear throughout the observed range (Table 10). A linear relationship between ruminal pH and NDF or ADF concentration was observed, and r^2 were similar to those reported by Erdman (42) who also observed that the relationship between ruminal pH and ADF concentration was linear. Pitt et al. (83) used data from sheep, beef cattle, and dairy cattle and observed a better relationship between eNDF and pH than between NDF and pH. They (83) also observed that the relationship between eNDF and ruminal pH reached a plateau at pH 6.4. For data from lactating cows, the high r^2 of the reciprocal regression suggests that a theoretical maximum plateau in pH near 6.5 to 6.7 occurred also (Figure 3 and Table 10).

The higher requirement for peNDF to maintain ruminal pH of 6.0 than to maintain 3.4% milk fat indicates the difficulty in defining an absolute requirement for fiber. Mertens (71) suggested that factors such as particle size and quality of the forage, NFC content of the ration, processing of grains, buffer feeding, and intake alter the minimum concentrations of forage and fiber in the ration. Allen (2) suggested that NDF requirements can vary ±5 units around a mean of 30% of ration DM. He provided specific recommendations for altering the NDF requirement when forage particle size varied; when nonforage fiber sources, buffers, or fat was fed; when ruminal starch or fiber digestibility or feeding frequency varied; and when variations in ration composition resulted from variable quality of ingredients. A similar approach may be needed with peNDF and eNDF requirements, but the variation (± 1 to 2 units) will be less than for NDF (Tables 9 and 10). Most of the variation associated with chewing activity, such as physical form and fiber concentration, should be accounted for by using peNDF. As more data from the literature are analyzed and as additional experiments are conducted using peNDF, more specific recommendations can be developed for unique feeding situations.

Source of concentrate (ground corn, rolled barley, rolled high moisture corn, ground mixtures of ingredients, and pelleted mixtures of ingredients) was included in the regression models as a class variable to determine whether they would affect ruminal pH independently of peNDF. Although the regression coefficients for source indicated that ruminal pH was highest for cracked corn, followed in order by rolled high moisture corn, ground corn, rolled barley, and pelleted mixtures of feeds, the coefficients were not different ($P < 0.05$) from one another when differences in peNDF were taken into account.

CONCLUSIONS

Current NRC (77) recommendations for fiber requirements of dairy cattle can be improved by adjusting fiber for its effectiveness in maintaining chewing activity, ruminal pH, and milk fat percentage. A system is proposed that distinguishes between the physical effectiveness of NDF to stimulate chewing activity and the overall effectiveness of NDF in maintaining milk fat percentage. Factors for converting NDF to peNDF can be derived from chewing activities associated with the intake of NDF from various sources. These factors can be used to estimate the peNDF of rations of cows fed a variety of fiber sources. Using this approach, the requirement for peNDF of dairy cows was determined to be 22% of ration DM to maintain an average ruminal pH of 6.0 and 20% of ration DM to maintain the milk fat percentage of early to midlactation Holstein cows at 3.4%.

Laboratory methods can be developed to estimate peNDF. At present, eNDF can be assessed only by lactation experiments, but a relationship between peNDF and eNDF may be possible as more data become available. Fiber is an important characteristic of feeds that can be used to formulate optimal rations. Adjustment of NDF for effectiveness provides a means of fine-tuning ration formulation for dairy cows. Either peNDF or eNDF can be used to determine the lower limit of F:C in the ration (something NFC can also accomplish), but this adjustment for effectiveness is the only way to formulate rations accurately when the physical form of the rations, but not the NFC concentration, is changed.

More research is needed 1) to standardize particle size measurements of feeds and forages and to relate particle size to chewing activity and peNDF; 2) to develop and test laboratory methods of assessing peNDF and eNDF that can be used to determine the effectiveness of individual lots of feed; 3) to develop relationships between eNDF and peNDF so that a method of assessing eNDF in the laboratory can be developed; 4) to determine whether long grass hay is the best reference standard for assessing physical effectiveness; 5) to measure the peNDF and eNDF of specific feeds, especially nonforage fiber sources, by measuring both chewing activity and milk fat depression in relation to long grass hay or comparable reference standards; 6) to identify whether differences in concentrate source, supplemental buffers, forages sources, concentration of fat in the ration, feeding frequency, and type of ration (total mixed versus separate feeding) affect the requirements for peNDF and eNDF; 7) to determine whether the peNDF requirement for animal health and longevity is different from requirements to maintain milk fat percentage or ruminal pH; and 8) to identify other chemical and physical characteristics of feeds that influence their effectiveness in maintaining optimal ruminal function and animal welfare.

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